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INFRARED DAMAGE DETECTION SYSTEM (IDDS) FOR REAL-TIME, SMALL-SCALE DAMAGE MONITORING

George A. Hartman

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14. ABSTRACT

Macroscopic damage and final failure of components subjected to repeated loading is preceded by microscopic damage accumulation in localized areas of the component material. The microscopic damage accumulation phase often comprises the majority of the life of the component. Thus, a detailed understanding of the processes involved would be invaluable for material design and life prediction. In metals, these localized damage accumulation areas are usually on the scale of the microstructure and the damage is not readily apparent. An infrared camera system has been developed to detect the radiant energy associated with local damage accumulation. This system pinpoints the location of the damage accumulation site and allows the loading to be stopped early in the damage accumulation process. The first goal is to use the system to stop mechanical testing as soon as a local damage area can be detected. This goal has been achieved and the IDDS has been used to support a number of research programs studying crack initiation. The second goal is to develop an understanding of the various phenomena that produce infrared radiation signatures and correlate them with damage accumulation mechanisms. This work is just beginning and this paper discusses our plan to meet this goal.

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Infrared Damage Detection System, IDDS, damage accumulation, infrared radiation, material behavior

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INFRARED DAMAGE DETECTION SYSTEM (IDDS) FOR REAL-TIME, SMALL-SCALE DAMAGE MONITORING

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ABSTRACT

Macroscopic damage and final failure of components subjected to repeated loading is preceded by microscopic damage accumulation in localized areas of the component material. The microscopic damage accumulation phase often comprises the majority of the life of the component. Thus, a detailed understanding of the processes involved would be invaluable for material design and life prediction. In metals, these localized damage accumulation areas are usually on the scale of the microstructure and the damage is not readily apparent. An infrared camera system has been developed to detect the radiant energy associated with local damage accumulation. This system pinpoints the location of the damage accumulation site and allows the loading to be stopped early in the damage accumulation process. The first goal is to use the system to stop mechanical testing as soon as a local damage area can be detected. This goal has been achieved and the IDDS has been used to support a number of research programs studying crack initiation. The second goal is to develop an understanding of the various phenomena that produce infrared radiation signatures and correlate them with damage accumulation mechanisms. This work is just beginning and this paper discusses our plan to meet this goal.

BACKGROUND

In metals, damage accumulation taking place under repeated loading has traditionally been viewed as two separate processes. The first process is an incubation stage where microscopic, irreversible damage accumulates to produce some macroscopic damage feature. The second process is the growth of the macroscopic damage feature to final failure. The crack propagation process can be modeled and the life of the component in this phase can be predicted with reasonable accuracy. The incubation stage, however, is usually treated as a “black box” with only one associated parameter - the number of loading cycles required to produce the macroscopic damage feature. In reality, even our limited understanding indicates that this initial damage accumulation is quite complex and varies greatly between different materials and loading conditions. Since the incubation period often constitutes the bulk of the usable service life for a component, studying the damage mechanisms associated with the incubation of macroscopic damage is clearly of great importance.

Of the many challenges in studying this small-scale damage, three merit our attention here.

1) The characteristic size of local damage regions is quite small, often less than 10 microns.
2) We don’t know *a priori* where the critical local damage region will be.
3) The measurable changes associated with the initial damage accumulation mechanisms are generally very small.

The first two challenges require instrumentation with a very large spatial dynamic range. That is, the measurement system must be able to monitor large areas while still detecting signal changes in very small areas. In a typical laboratory specimen, we may wish to monitor an area that is 10 mm square. If the local damage regions are only 10 μm square, we need to continuously monitor 10^6 local regions to be sure we catch the damage we are interested in. The third challenge requires highly sensitive and stable measurements to resolve the small signal changes we anticipate from the initial damage accumulation processes. Successfully developing instruments with wide dynamic range, high sensitivity, and excellent stability is generally considered the trifecta of experimental challenges.

The University of Dayton Research Institute (UDRI) and The Air Force Research Laboratory (AFRL) have collaborated to develop an instrument capable of monitoring damage accumulation prior and subsequent to small crack formation in various metal alloys used in turbine engines. The system comprises an infrared camera and microscope coupled with frame grabber

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hardware and test control and image manipulation software. The system monitors changes in infrared radiation in real-time as cyclic loads are applied to the test specimen. This article describes the system details, the current methods used to detect local damage regions, and work underway to enhance the capabilities of the system.

INFRARED DAMAGE DETECTION SYSTEM (IDDS)

The IDDS system is shown schematically in Figure 1. The essential elements are:

- a test specimen to which we will apply cyclic loads
- an infrared camera viewing the specimen,
- a microcomputer with interface hardware to generate the waveform and sync signals and capture the image frames from the camera, and
- a software package to control the test, analyze the data, and store the results.

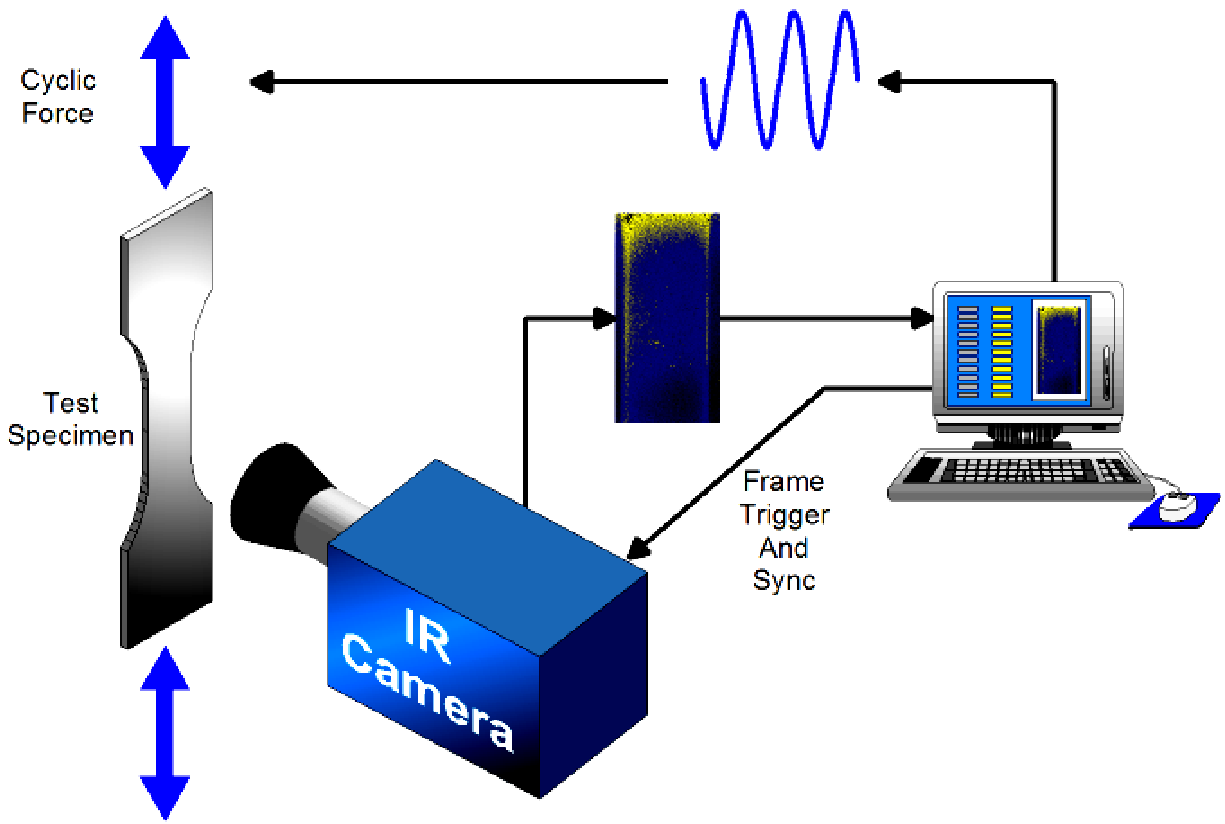

Figure 1. Infrared Damage Detection System (IDDS) Overall System Schematic.

Materials and Specimen Geometries

IDDS development to this point has been done in conjunction with several different research programs that could potentially benefit from IDDS results. Thus, the specimens used in developing the IDDS have been fabricated from a number of materials including titanium alloys, titanium-aluminide intermetallics, and nickel-base superalloys. Various geometries have also been used; however, we will focus on the geometry illustrated in Figure 2 for our discussion since it is representative. Specimen surface preparation generally consists of either electropolish, or low-stress grind followed by hand polish to the sub-micron level. Specimens are carefully cleaned prior to testing as any small debris on the surface produces a large infrared signature.

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Infrared (IR) Camera

The IR camera works in the same manner as a common consumer digital camera except that the detectors are designed to be sensitive to longer wavelengths (and the hardware is substantially more expensive!). We are currently using two different IR cameras in our laboratory. The first camera has a resolution of 256 x 256 pixels at 12 bits per pixel. The second camera has a resolution of 640 x 512 pixels at 14 bits per pixel. These particular cameras are being used primarily because they are available to us. Cameras with similar wavelength sensitivity have been successfully used by other researchers [1, 2] for related work, but the optimum wavelength sensitivity for our work is certainly an area that merits further study.

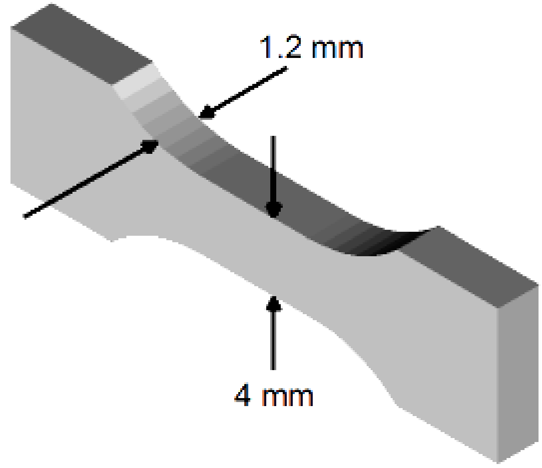

Figure 2. Typical Specimen Geometry.

The effective resolution of the of the individual camera detectors (pixels) is of prime importance since we are looking for small deviations from the average radiation in a local region. Studies of the scatter in individual pixel outputs under typical test conditions show a Gaussian distribution for the individual readings and a standard deviation of approximately 10 bits. Averaging individual pixel readings from multiple frames reduces the output standard deviation as shown in Table 1. As shown in the table it is possible to obtain sub-bit effective resolution if a sufficient number of frames are available for averaging.

Table 1. Effect of Frame Averaging On Pixel Output Standard Deviation

Frames Averaged	Approximate Pixel Output Standard Deviation (bits)
1	10
10	3
100	0.8
500	0.15

The internal IR camera control system works with frame integration times rather than the shutter speed as is commonly done in optical photography. The integration time is the inverse of the shutter speed. Increasing the integration time reduces the noise in the camera output but also reduces the maximum temperature that will saturate the detectors. For room-temperature studies, we use an integration time of 1 ms which saturates the detectors at approximately 40 ºC when viewing a polished metal surface. Surfaces with a higher emissivity would require a shorter integration time. A 1 ms integration time combined with the polished metal surfaces yields a temperature resolution of approximately 25 mK per bit for the 12 bit camera and 14 mK per bit for the 14 bit camera. A typical calibration graph is shown in Figure 3.

Just as in optical photography, the integration time (or shutter speed) is also important if the image changes with time. In our case, we wish to capture a snapshot of the test specimen at essentially a single point in the loading cycle. Using a 10 Hz sinusoidal loading cycle with a 1 ms integration time means we are looking at the integrated image over 1/100th of the cycle. Experience shows that this is a sufficiently small section of the loading cycle to produce good results. Longer integration times tend to smear out changes in the image just as using too slow a shutter speed in an optical camera blurs the photo.

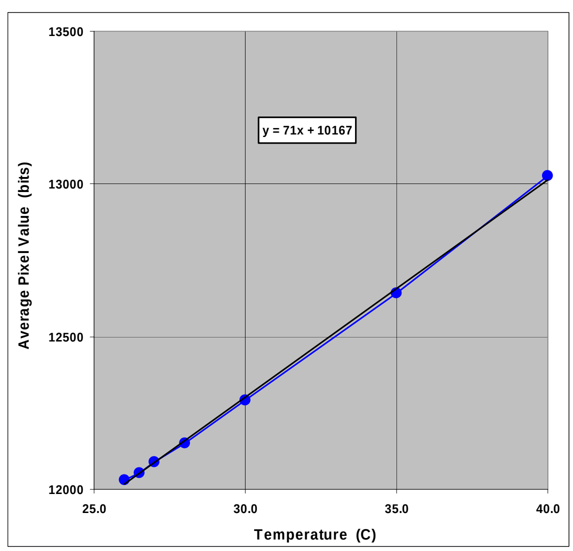

Figure 3. Typical Temperature Calibration With Polished Stainless Steel

As seen in Figure 2, the representative specimen width is about 4 mm. Using our 1X microscope optics, an IR image from our 14-bit camera encompasses an area approximately 10 mm square. Within this 10 mm square image we see a 10 mm high by 4 mm wide section of the test specimen. Thus, with our high-resolution camera, this section of the specimen is roughly 512 pixels high by 256 pixels wide. Each pixel images an area on the specimen surface approximately 20 μm x 20 μm. If necessary, the optical magnification can be increased so that we view a specimen area about 2.5 mm square and each pixel images an area on the specimen surface approximately 5 μm x 5 μm. The magnification can also, of course, be reduced to image much larger areas.

For our local damage detection purposes, we do not need to resolve details in the local damage region. It is sufficient that the damage in the local region causes at least one of our camera pixels to change intensity sufficiently that we can detect the change through the background noise. This is a huge advantage since we can use considerably lower spatial resolution on the specimen surface than would be required in a typical optical or SEM image where the local damage might only be discernable provided the local details are resolved.

What the IR Camera Measures

The IR camera records the magnitude of emitted radiation within its bandwidth. The magnitude of the emitted radiation is usually assumed to be simply a function of the specimen surface temperature, but is actually a function of a number of phenomena including, but not limited to, temperature, surface emissivity, reflected radiation, and cavity radiation.

Since some of these phenomena have multiple underlying mechanisms, an infrared image will, in general, contain a combination of information from a variety of physical phenomena. In our cyclic loading tests for example, the specimen surface temperature will change due to thermoelastic stresses, irreversible (inelastic) deformation, or simply from temperature changes in the surrounding environment. In addition, any surface-connected voids or cracks in the material are potential sources of cavity radiation effects and the highly reflective surface of the polished metal easily produces reflected radiation that may enter our camera.

Microcomputer System

The microcomputer system we are currently using is a standard personal computer with a 2.8 GHz processor, 1 GB of RAM, a 200 GB hard drive, and a large format monitor. The following interface boards have been added.

- Digital frame grabber
- Analog-to-digital (A/D) converter
- Digital-to-analog (D/A) converter
- Counter/timer/digital I/O

Image processing is handled primarily by the PC CPU at this time since we have not yet established the optimum image processing methods for various types of damage detection. We hope to offload this chore to a dedicated DSP unit once we have a better handle on the specific types of tasks we will be performing. Never-the-less, the performance of the standard PC CPU is surprisingly good even when manipulating a large number of images.

Software Package

Real-time test control, data collection, image processing, and operator interface functions are provided by the WinMATE© material test automation package. The IDDS software has been developed as a test application module within WinMATE. WinMATE provides an internal suite of routines for point-by-point waveform generation, image synchronization, FFT, and other functions necessary for IDDS testing.

GENERAL EXPERIMENTAL PROCEDURES

Up until the past few months, the general experimental procedure using the IDDS has consisted of applying a cyclic load to the specimen, collecting sets of infrared images at specified cycle intervals, analyzing the images, and stopping the test if an anomaly is detected. We have been successfully using the IDDS in this manner to detect cracks smaller than 20 μm surface length on a daily basis for more than three years. An example of a processed infrared image and the associated surface crack is shown in Figures 4a and 4b with the local damage area denoted by the red circle in 4a. In a number of cases, no surface-connected crack can be found although the IDDS shows definite local damage accumulation. We suspect these results may reflect local inelastic deformation prior to crack nucleation or, perhaps, a sub-surface crack.

The images acquired and image processing performed for this work is based on the knowledge that the thermoelastic temperature change is a significant component of the overall infrared radiation signature during cyclic loading [3]. Images are acquired at the maximum and minimum loads and subtracted to produce a composite image. A significant number of additional processing steps are applied to these composite images including image averaging and differencing across ranges of cycles. These steps reduce the infrared background and pixel noise and, in conjunction with specialized local-area threshold detection algorithms, allow us to detect the initiation of very small cracks or even crack precursors.

This thermoelastic-based method has been remarkably successful in detecting the onset of cracking and producing specimens at various stages of damage evolution. Furthermore, these specimens can be studied in detail post-test using in-depth metallographic methods since the IDDS precisely locates the damage site or sites.

Despite this success, we still do not have a good understanding of how the various known sources of infrared radiation interact and how they appear in our infrared images during mechanical cycling, nor how they are related to damage accumulation mechanisms in the material. Obtaining this understanding is the goal of the current phase of IDDS development.

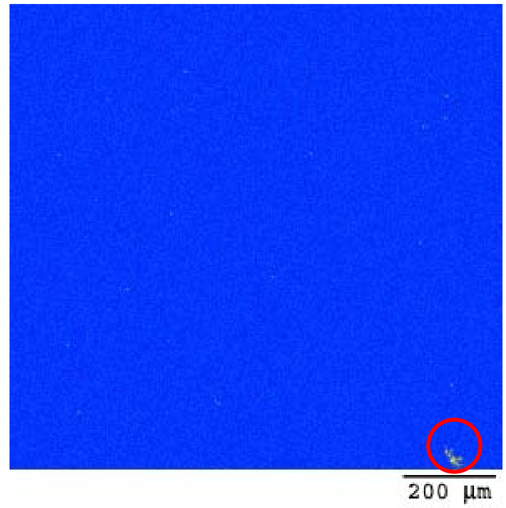

Figure 4a. Processed Infrared Image Of a Small Surface Crack.

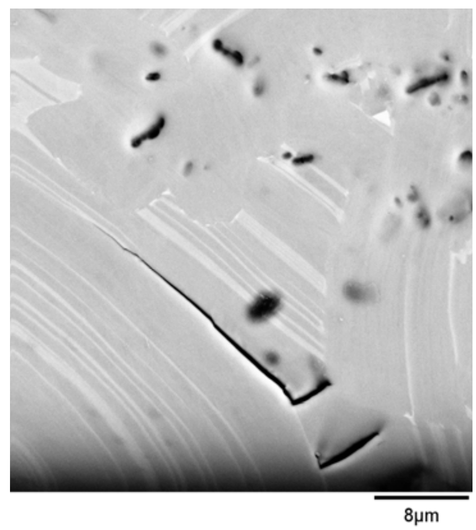

Figure 4b. SEM Image Of the Surface Crack in Figure 4a.

Finding the Right Images and Algorithms

How and where in the loading cycle we acquire infrared images, and how we process them, is dictated by the need to minimize some of the phenomena discussed above and accentuate others. Knowing which phenomena to minimize and which to accentuate requires that we know which phenomena are associated with various damage accumulation mechanisms. Some of this information we can obtain from basic physics, mechanics, or fracture mechanics, and some is best obtained by studying the effects of various phenomena on the image as seen by the camera. For example, in a local area with a large amount of inelastic deformation we might, as a minimum, expect the following.

1. In each loading cycle, there will be two bursts of heating – one associated with inelastic loading deformation and one with inelastic unloading deformation.
2. There will be global thermoelastic temperature changes wherein the global specimen temperature will be coolest at the maximum stress and hottest at the minimum stress.
3. If a small crack is present, the local thermoelastic effects will be complicated since the material at the crack plane midway between the crack tips will be essentially unloaded throughout the cycle.

There may be, of course, additional effects. For example, cracks often initiate from pores in the material which may produce cavity radiation effects.

We know that we must obtain images at appropriate points in the loading cycle and process them properly to open the possibility of observing the various phenomena we've discussed and gaining an understanding of their underlying mechanics. To that end, The University and AFRL have initiated a program to collect an extremely broad infrared image library which can be analyzed in any desired way to test different processing methodologies. As of this writing, the first section of the image library has been collected and partially analyzed. These preliminary results are presented in the remainder of this paper. Additional sections of the library are currently being collected.

PRELIMINARY INFRARED IMAGE LIBRARY ANALYSES

Before discussing the current IDDS work on the preliminary image library analysis, several points should be noted. First, all images in this paper are by definition false-color since humans are unable to see infrared radiation directly. For comparison purposes, all images in the remainder of this paper use the same color palette. Second, the data set we will discuss contains cracks much larger than the detection threshold of the IDDS. This was done so that the local damage regions would be readily visible in the printed versions of the images we will present. Third, as previously discussed, the camera records infrared radiation which is not necessarily correlated with temperature. Therefore, we will use the term "equivalent temperature" to refer to radiation values that have been converted to temperature as if no other sources of radiation were active. Finally, although the format of the images we present makes large radiation anomalies visible, the mathematical algorithms used to detect local damage can generally "see" the local damage long before it becomes evident in the images.

The first section of the image library has been obtained from an Inconel 100 alloy specimen cyclically loaded at a stress ratio of 0.1 and a maximum stress near the proportional limit. 200,000 loading cycles were applied to this specimen and image sets were acquired approximately every 50 cycles. Each image set consisted of 20 infrared images evenly spaced in time over the loading cycle. Thus, section 1 of the image library comprises:

- 200,000 cycles
- 200,000 cycles / 50 = 4,000 image sets
- 4,000 image sets x 20 images per set = 80,000 images
- 80,000 images x 640 x 512 x 2 bytes per pixel = ***49 GB***

All of these raw infrared images are available on desktop workstations and can be analyzed using whatever method the researcher deems most appropriate. Obviously, there are a huge number of ways to analyze them depending on the desired results and assumptions made about the underlying mechanisms.

Perhaps the most obvious initial route to take is to see if improvements can be made in the image processing for damage detection we have been using for the past few years. With that goal in mind, we processed the images using the algorithm which is currently built into the WinMATE test control module. The final processed image at 200,000 cycles resulting from this analysis is shown in Figure 5. The damage detection routine was then applied to the images and the red circles in Figure 5 indicate two of the regions where local damage accumulation was detected. Although there were a number of other local damage sites detected, these two are circled since they are the only ones readily visible in the infrared image shown here.

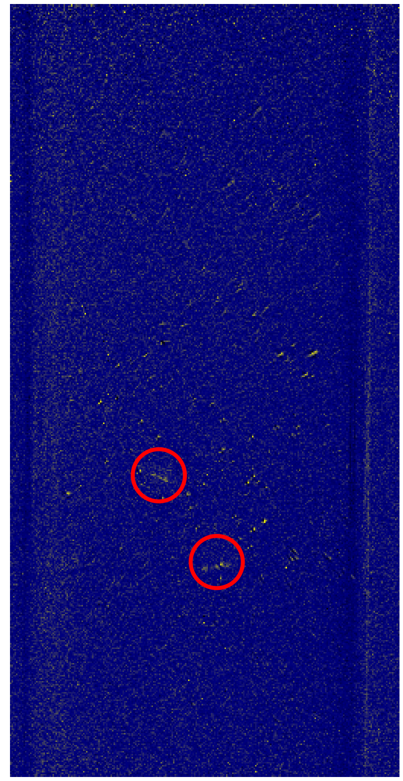

Figure 5. Image Resulting From Original Processing Algorithm.

The first alternate method of image processing we attempted was to simply subtract the image taken at the maximum load on the first cycle from each image taken at the maximum load in subsequent image sets. The last image in this series (at 200,000 cycles) is shown in Figure 6. Note that the two damage regions marked in Figure 5 are more clearly visible and a third damage region is also visible in the region between them. We next performed the same type of processing using the images taken at the minimum load in the cycle. These results are shown in Figure 7 and the three damage areas are even more clearly visible. The actual maximum equivalent temperature increase for the lower damage region in Figure 7 is approximately 110 bits or about 1.5 K. Again, we note that this is a very large temperature change compared to the 20 to 50 mK change normally associated with initial detection by the original WinMATE algorithm.

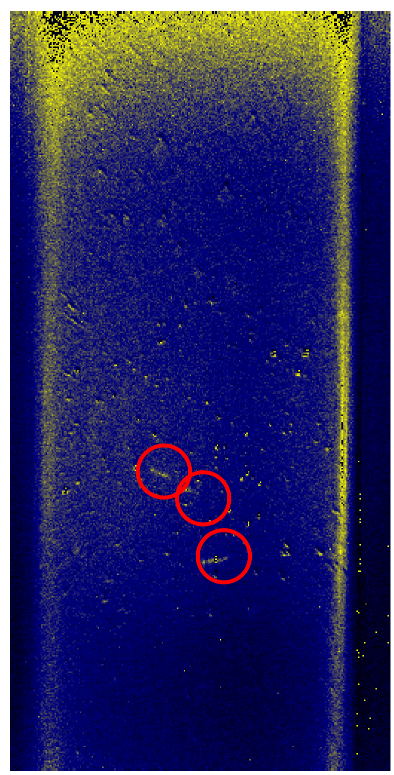

Figure 6. Differential Image at Maximum Load.

At first glance, the results of these two simple differencing processes seem to indicate they are superior to the original image processing method for detecting local damage evolution. Note, however, that all of the circled damage regions represent relatively large cracks of surface length greater than 250 μm. Thus, we are seeing infrared radiation associated with larger propagating cracks rather than radiation associated with the incubation of a small crack. The other local damage regions detected by the original image algorithm which are not visible (or circled in the figures) correspond to cracks that are considerably smaller and, in some cases, to regions where no crack is visible.

We must keep in mind that the infrared signatures of local damage regions are complex combinations of cycle- and load-dependent phenomena. Image processing methods suited to monitoring propagation of larger cracks may not be suitable for local damage detection as demonstrated by Figures 5 through 7. In fact, we would expect the physical phenomena associated with small crack evolution to be different from the phenomena associated with larger crack propagation and therefore, we should not expect the infrared signatures of these two processes to necessarily share common features.

Figure 8 contains a montage of photos from an acetate replica taken from the specimen surface at the end of the 200,000 loading cycles. The figure clearly shows the three damage areas visible in the infrared images as well as a number of other artifacts such as those shown in the blue and green circles. Closer inspection of duplicate replicates and the specimen surface shows the features in the blue circles to be artifacts of the replication process (wrinkles, etc.) and not actual specimen surface features. The green circles, however, represent cracks that are not readily visible in the infrared images resulting from any of the three processing methods described above. We should note that, although these features are not visible in the infrared images, they were detected by the original damage accumulation detection algorithm.

The additional artifacts in the replicate montage suggest that an alternative specimen imaging method would be advantageous for our work. One instrument we have used extensively for this purpose is the SEM. SEM photographs such as Figure 4b provide clearer and cleaner images of the specimen surface but they require us to remove the specimen from the test system. Once the specimen is removed, it is nearly impossible to replace it in the same position with sufficient accuracy such that subsequent infrared images can be compared with those taken before removing the specimen. Thus, we have used the acetate replication technique at intermediate points in the 200,000 loading cycles to obtain a measure of the damage on the specimen surface while allowing acquisition of a continuous set of images for the image library.

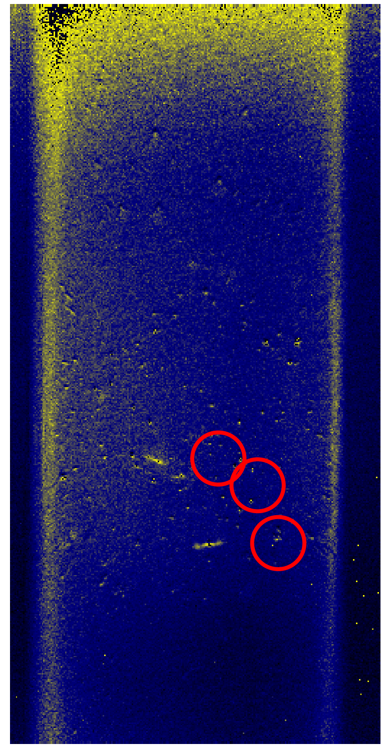

Figure 7. Differential Image at Minimum Load.

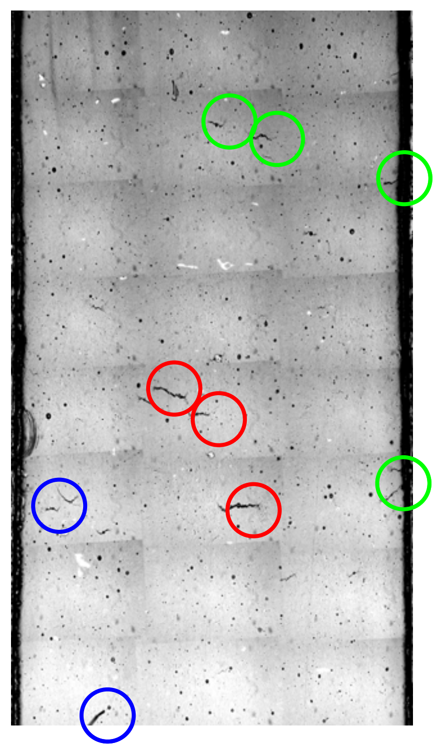

Figure 8. Photo Montage of Specimen Surface Acetate Replicate.

SUMMARY

An infrared damage detection system (IDDS) has been developed that is capable of identifying and locating regions of evolving damage in real-time. We have been using this system for several years to identify regions where crack precursor and small crack (≈ 20 μm surface length) damage are occurring.

Current work focuses on extending our understanding of the various sources of infrared radiation from specimen surfaces and the underlying physical phenomena. Initial efforts include collection of images forming the initial portion of a library to be used to evaluate various image processing methods. A great deal of additional work is required to optimize these image processing methods for various purposes and to understand the relationship between various infrared signatures and the associated material behavior.

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